Connecting the Dark Side and Fundamental Physics

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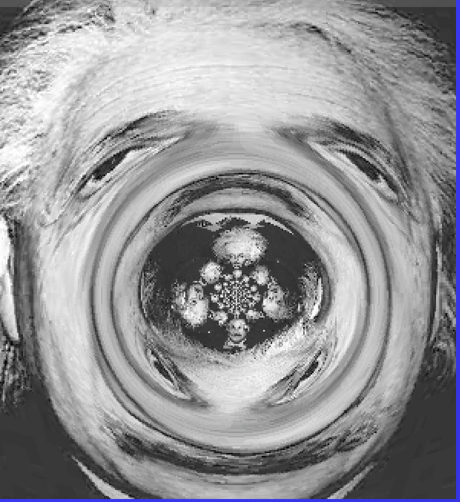
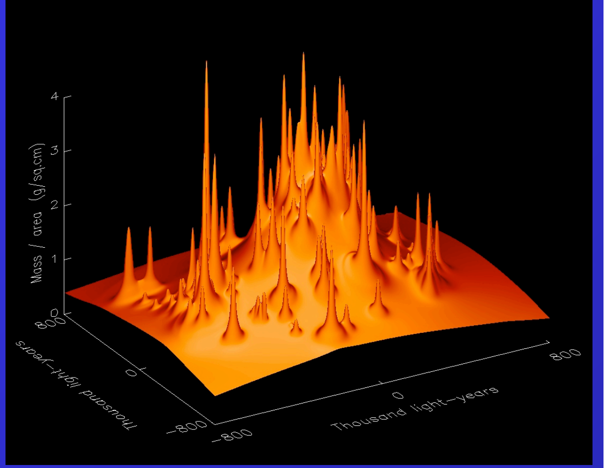
Outline

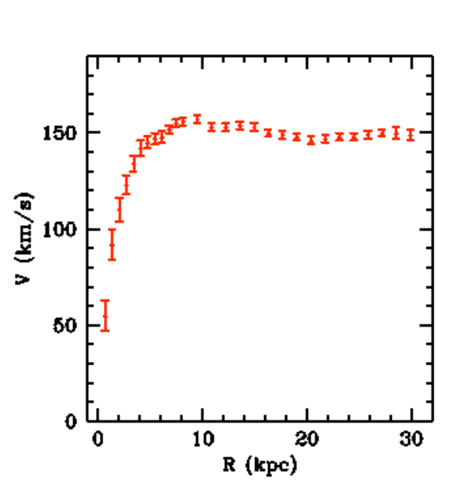
- Accounting for the Energy Budget of the Universe
- Mysteries of the Pie Chart
  - Dark Matter; the Baryon Asymmetry; Cosmic Acceleration
- Connecting Cosmology and Fundamental Physics
  - TeV Scale Physics, the Hierarchy Problem and Dark Matter
  - TeV Scale Physics and the Baryon Asymmetry
  - What About Dark Energy?

Particle physics and cosmology, as disciplines independent of one another, no longer exist.
Our most fundamental questions are now the same and we are approaching them in complementary ways.

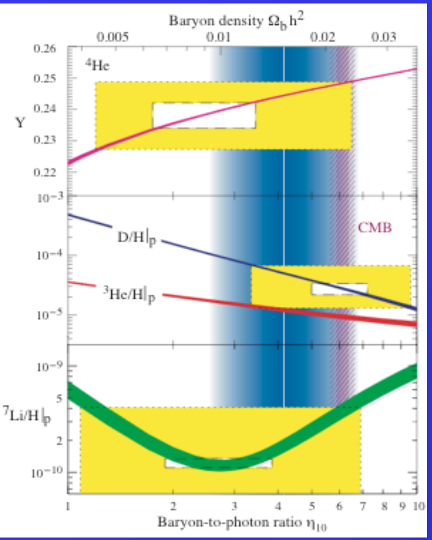




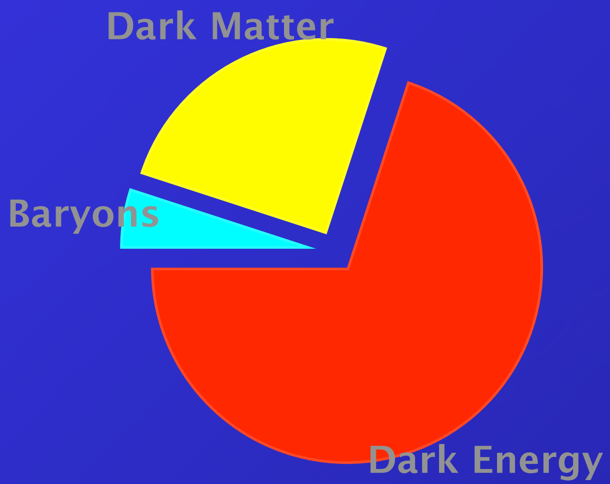
Mass / area (g/sq.cm)
Thousand light-years
Thousand light-years
800
0
-800



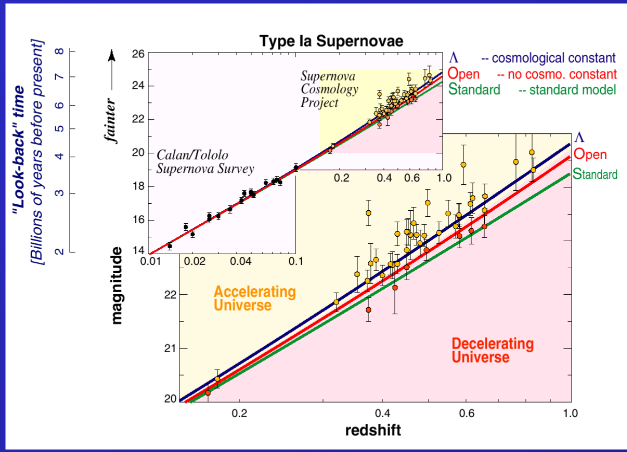
V (km/s)
R (kpc)



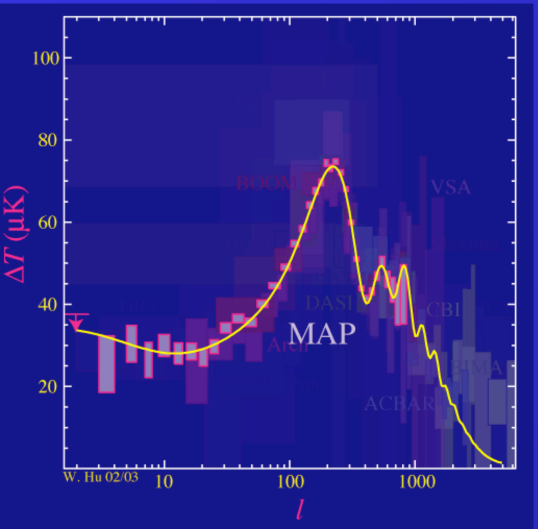
Baryon density $\Omega_b h^2$
^{4}He
Y
D/H|p
^{3}He/H|p
CMB
^{7}Li/H|p
Baryon-to-photon ratio η_{10}



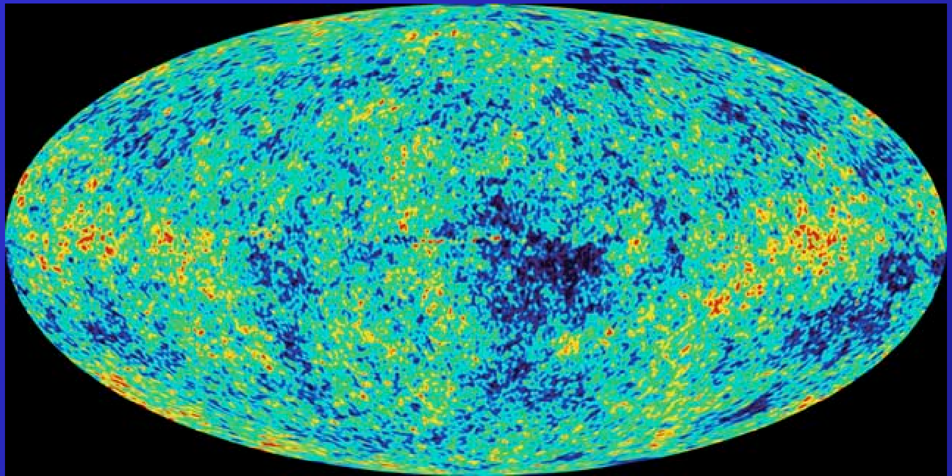
Dark Matter
Baryons
Dark Energy

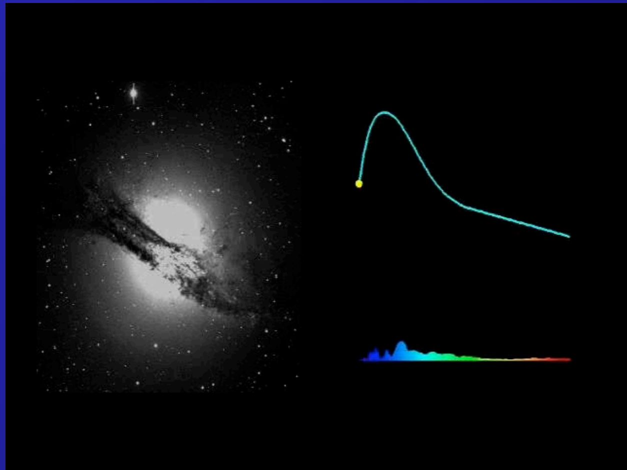


Type Ia Supernovae
Λ -- cosmological constant
Open -- no cosmo. constant
Standard -- standard model
"Look-back" time
[Billions of years before present]
fainter
magnitude
Supernova Cosmology Project
Calan/Tololo Supernova Survey
Accelerating Universe
Decelerating Universe
redshift



ΔT (μK)
MAP
BOOM
VSA
DASI
CBI
Archeops
ACBAR
W. Hu 02/03
l

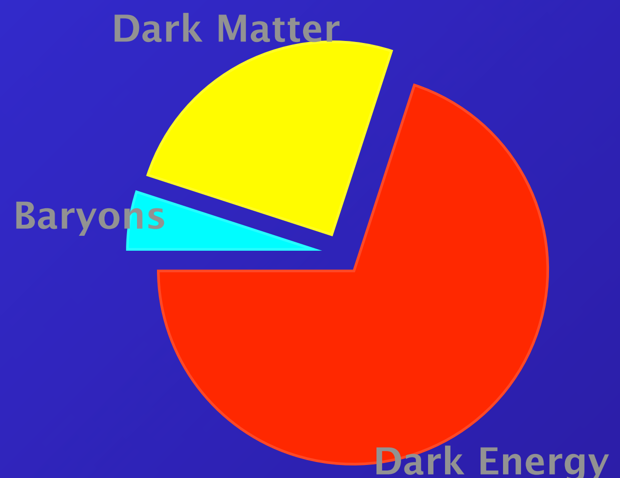




We don't know what these particles are but we have some well-motivated ideas

[See Dan Akerib's talk next]

We know what these particles are but not why they haven't met their antiparticles



We have absolutely no idea what this stuff is and we have no ideas that are well-motivated and well-developed!

Our Three Problems

- Three problems posed by observational cosmology.
- A great achievement, but raises many issues.
- Need fundamental physics to understand what the universe is made of and why these observations look the way they do.

The ALCPG Working Group on Cosmological Connections

http://www.physics.syr.edu/~trodden/lc-cosmology/

Editorial Committee:

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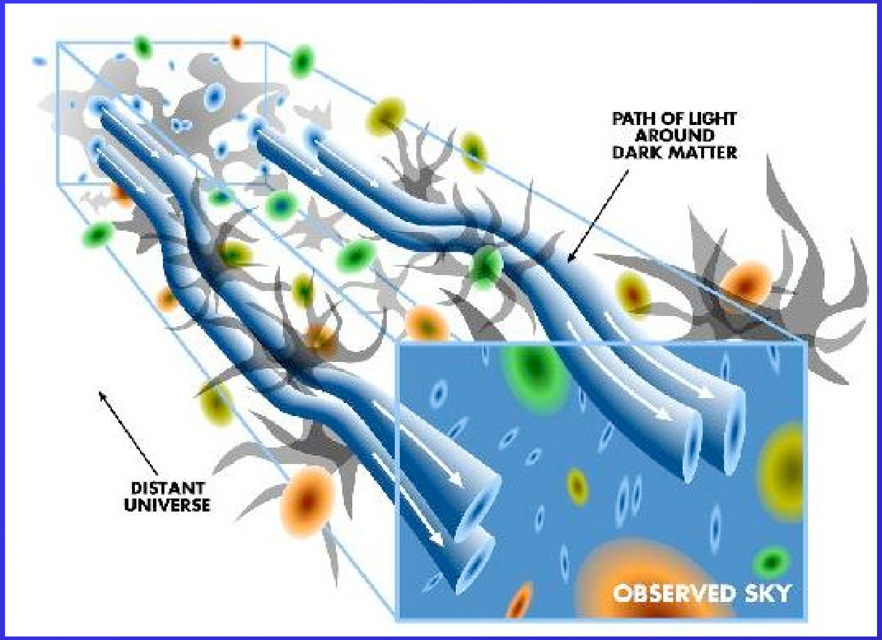
- Jonathan Feng (Irvine, co-Chair) jlf@uci.edu
- Norman Graf (SLAC)
- Michael Peskin (SLAC)
- Mark Trodden (Syracuse, co-Chair) trodden@physics.syr.edu

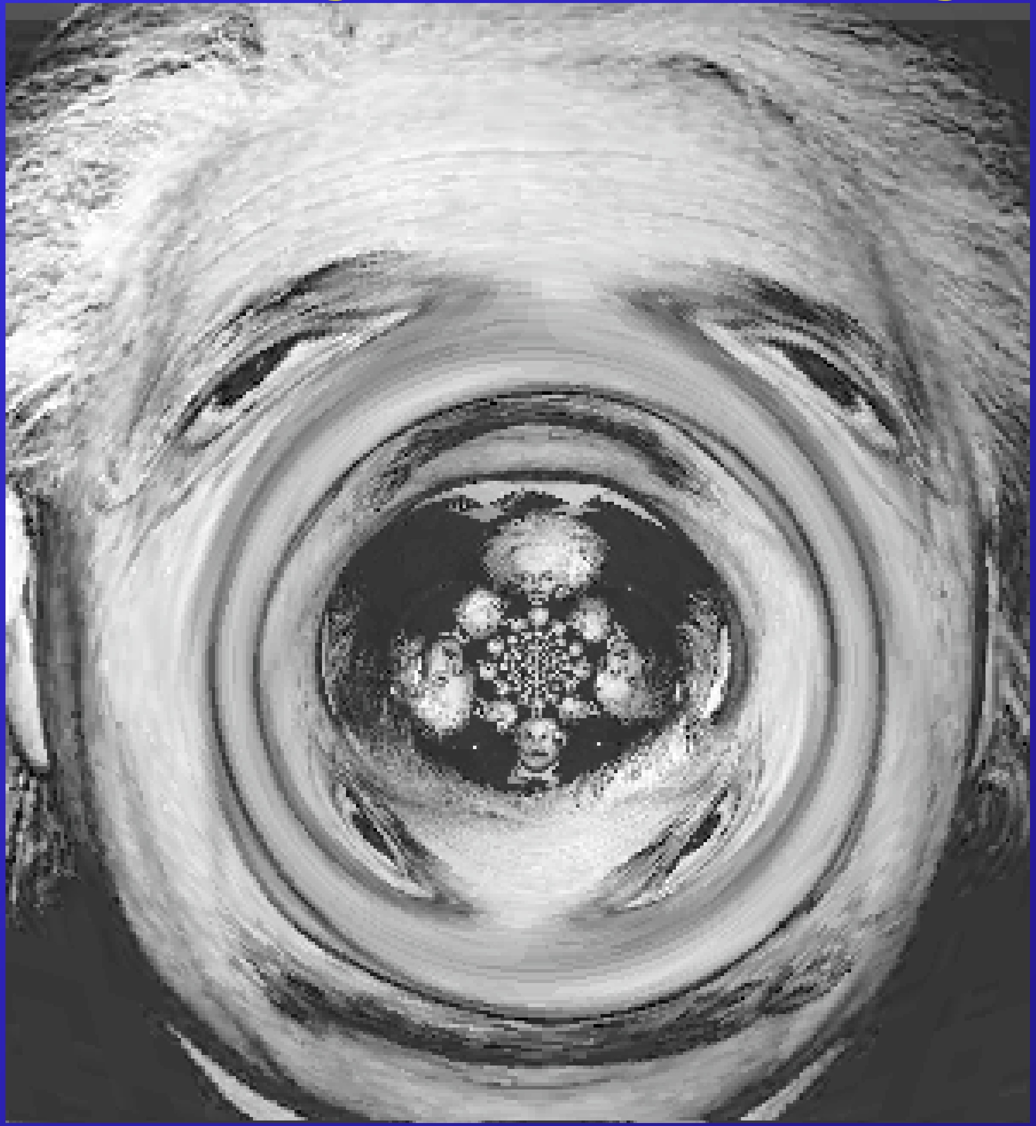
Have commissioned many new studies in addition to synthesizing existing results into a single coherent picture

Preliminary analyses were reported at LCWS 2005 at Stanford. White paper will follow around end of year

Dark Matter

- Originally noticed through galaxy rotation curves
- One modern way to look for it - weak gravitational lensing



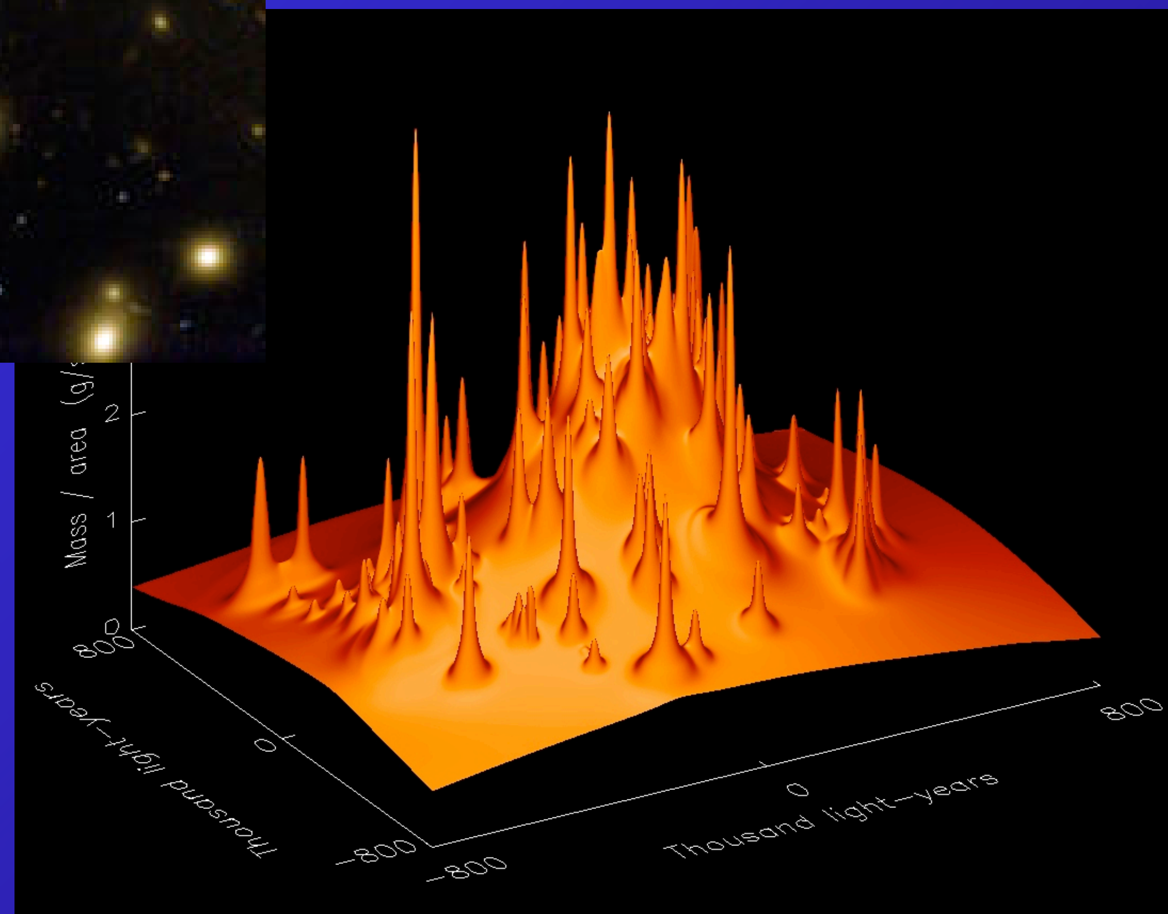


[See also Dan Akerib's talk next]

How to Use it

Can reconstruct the density in the cluster

$\boxed{\text{What is this stuff?}}$



- WIMPs?
- SUSY particles?
- Axions?
- Remnants of GUTs?
- ...

BSM Physics & Dark Matter

There is a very broad connection between models of beyond the standard model physics (particularly those addressing the hierarchy problem) and dark matter

- Almost any model involves new particles at the TeV scale, related to the SM particles through symmetries (SUSY partners, KK partners, extra gauge and scalar partners, ...)
- Typically, to avoid things like proton decay and precision EW tests, an extra symmetry is required (R-parity, KK-parity, T-parity, ...).
- This symmetry renders stable some new particle at the weak scale

Often, this stable new particle is an ideal WIMP candidate!

Dark Matter

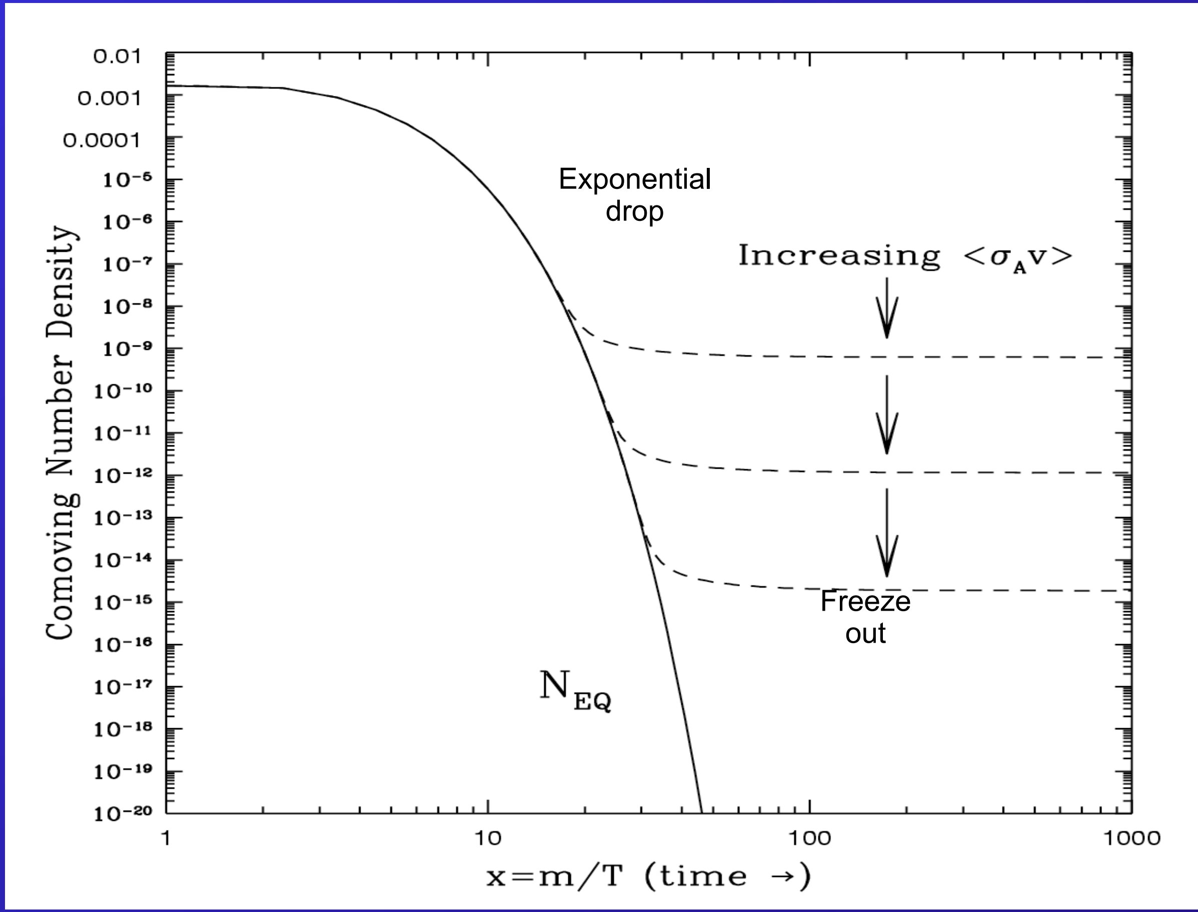
- A prime dark matter candidate is the WIMP
- → a new stable particle χ.
- Number density n determined by

$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left(n^2 - n_{eq}^2 \right)$$

Dilution from expansion

Annihilations

- Initially, <σv> term dominates, so $n \approx n_{eq}$.
- Eventually, n becomes so small that dilution term dominates
- Co-moving number density is fixed (freeze out).



[See Dan Akerib's talk next]

Abundance of WIMPs

Universe cools, leaves residue of dark matter with $\Omega_{DM} \sim 0.1\ (\sigma_{Weak}/\sigma)$

- Weakly-interacting particles w/ weak-scale masses give Ω_{DM}
- Strong, fundamental, and independent motivation for new physics at weak scale

- Could use the colliders as a **dark matter laboratory**
- Discover WIMPs and determine their properties
- Consistency between properties (particle physics) and abundance (cosmology) may lead to understanding of Universe at $T = 10$ GeV, $t = 10^{-8}$ s.

Can compare this program with the one that led (with spectacular success) to our understanding of BBN via a detailed understanding of nuclear physics

What are the PP Challenges?

- Definitive predictions depend on detailed studies.
- Mass and cross-section expectations depend on the modes of annihilation, determining the freeze-out abundance.

Can the LHC/ILC identify all the candidate thermal relics (and distinguish the various possibilities)?

- In SUSY (well, mSUGRA anyway) detailed studies exist
- In other models, one can currently only broadly quote typical values and bounds

Rough Examples

Model	DM Mass
Universal Extra Dimensions	~ 600 GeV
Branon Dark Matter	> 100 GeV
Randall-Sundrum Dark Matter	> 20 GeV
(insert favorite model here)	....

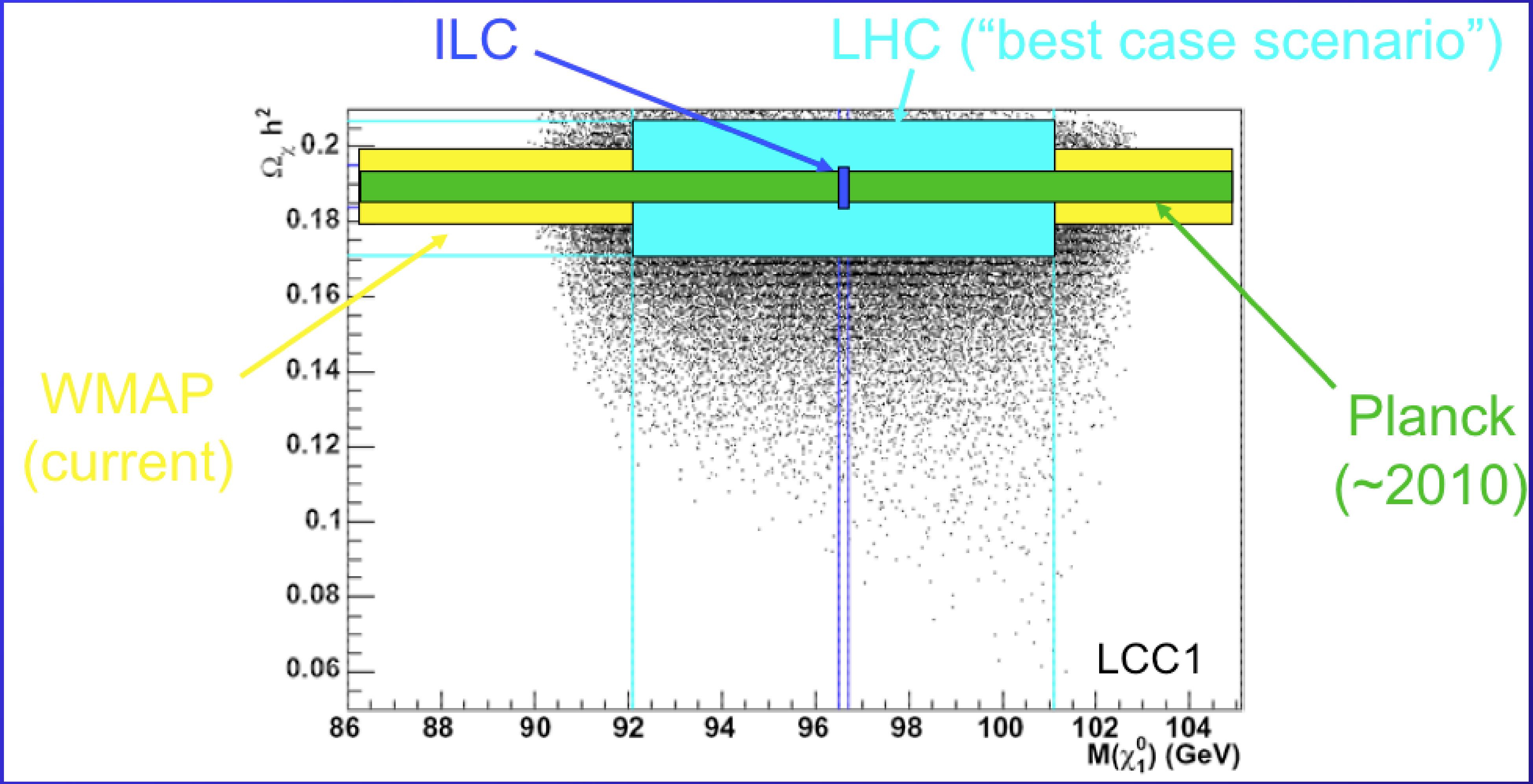
[Report will summarize new results for many of these]

- Initial stage of ILC already sensitive to large part of parameter space.
- Much theoretical effort needed to make precision predictions before ILC.
- Obviously helpful if a candidate is found at the LHC.

An Example (in mSUGRA)

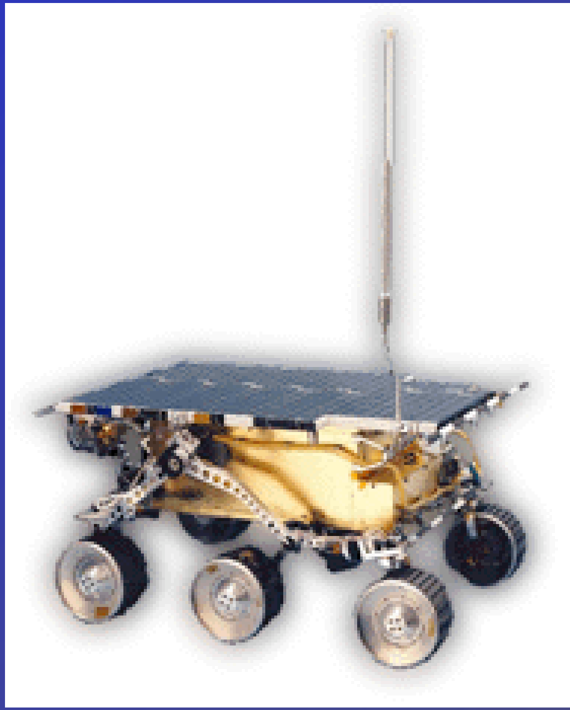
LCC1: the Bulk Region $\mu > 0\ ,\ \ m_{3/2} > m_{LSP}$

$$m_0 = 100 GeV\ ,\ \ M_{1/2} = 250 GeV\ ,\ \ A_0 = -100\ ,\ \ \tan\beta = 10$$



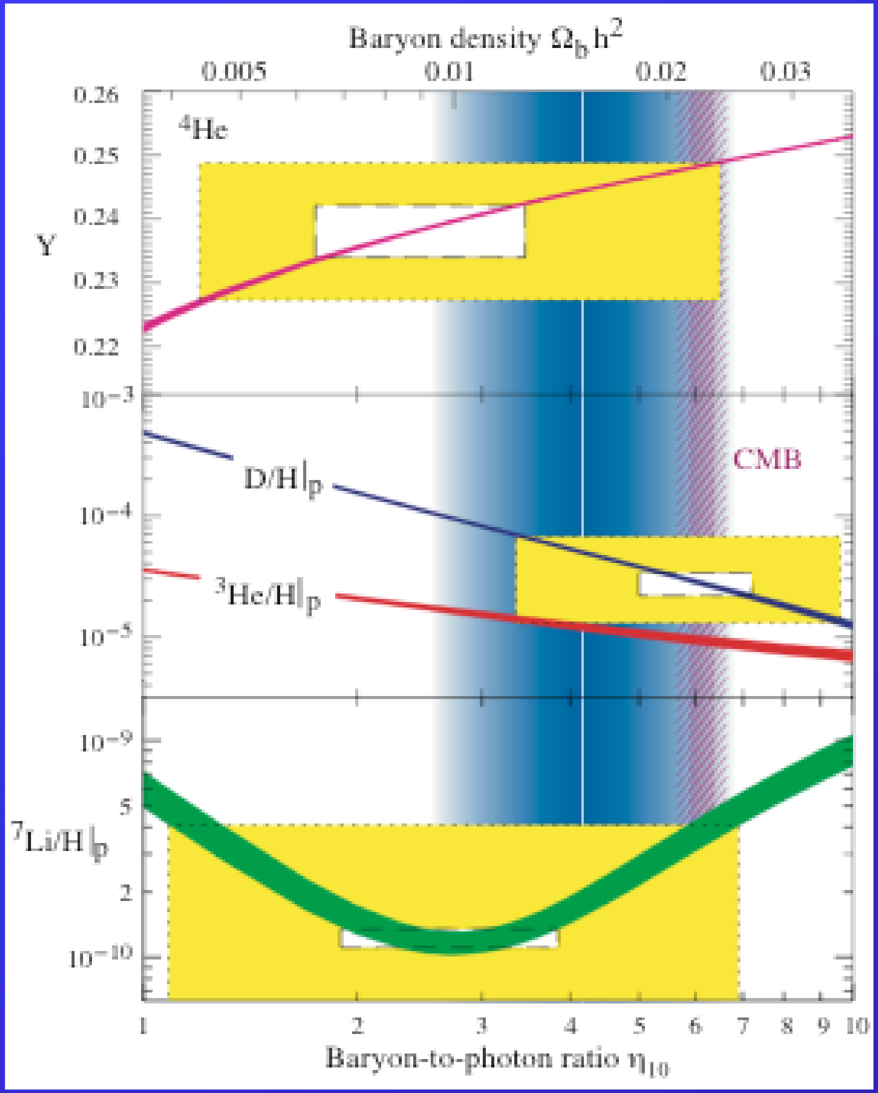
A Fundamental Problem

- Can construct a ladder of evidence



- Essentially, observable universe, out to the Hubble size, is made of matter and not antimatter (nice result from Cohen, De Rujula and Glashow)

Baryogenesis



BBN and CMB have determined the cosmic baryon content:

$\Omega_B h^2 = 0.024 \pm 0.001$

To achieve this a particle theory requires (Sakharov, 1968) :

- Violate Baryon number (B) symmetry
- Violate Charge and Charge-Parity symmetries (C & CP)
- Depart from thermal equilibrium
- (LOTS of ways to do this!)

A Connection to TeV Physics

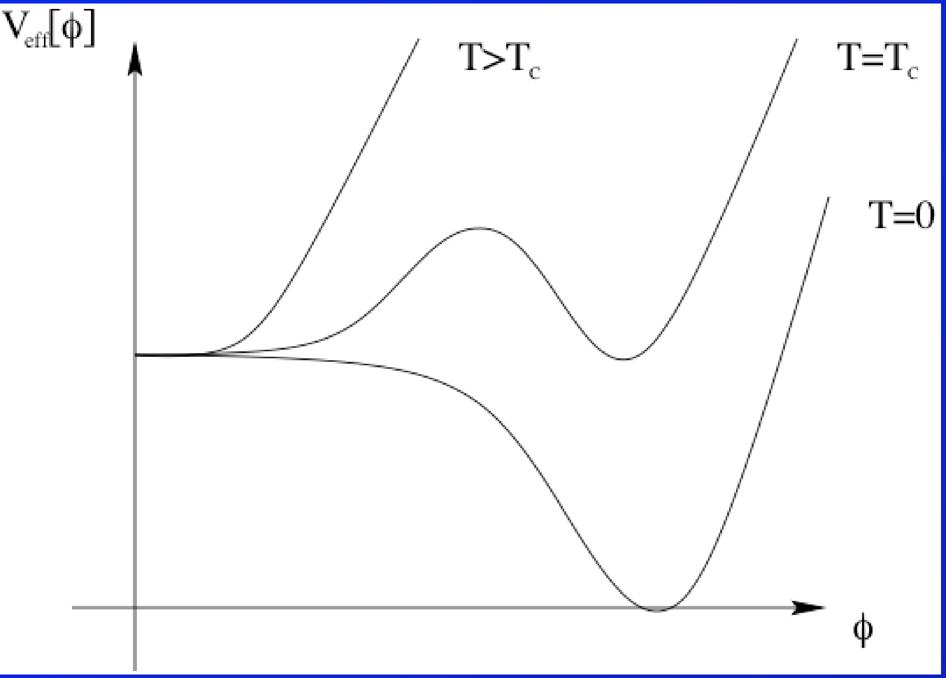
- Many scenarios for baryogenesis rely on physics at the GUT scale. In these cases the colliders have little to add.

- However, an attractive and testable possibility is that the asymmetry is generated at the weak scale.

- The Standard Model of particle physics, satisfies all 3 Sakharov criteria in principle, (anomaly, CKM matrix, finite-temperature phase transition)
- Exciting, but turns out not enough CPV and a continuous EWPT. Therefore, cannot be sufficient to explain the baryon asymmetry!
- This is a clear indication, from observations of the universe, of physics beyond the standard model!

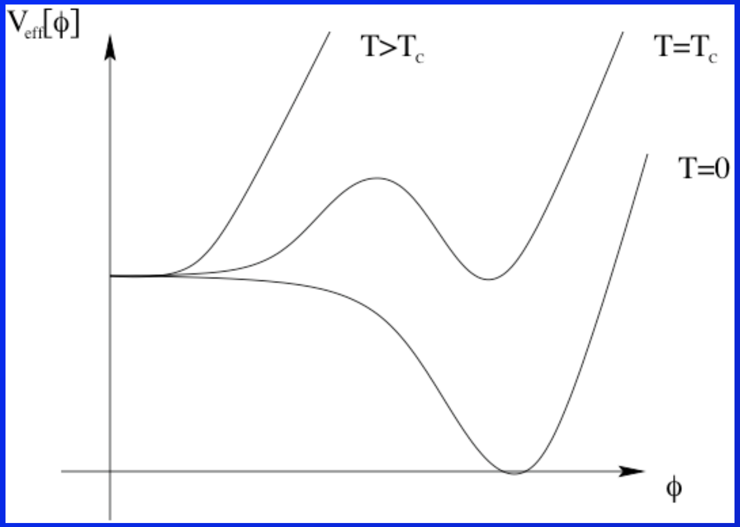
The Phase Transition I

- At high temp, EW symmetry restored: <ϕ>=0
- At low temp, <ϕ>=v=250 GeV
- At a critical temperature T_c, a phase transition occurs

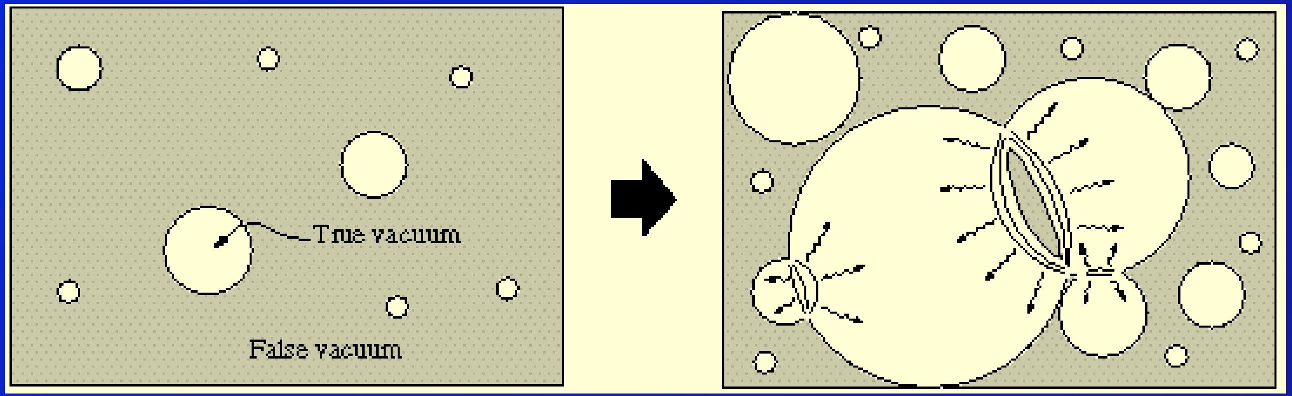


- Order depends on the presence of sufficiently light scalars
- For successful EWBG, usually need PT to be strongly 1st order to get required departure from equilibrium (and to avoid washout)
- In the minimal SM, there is only the Higgs to play with and it would need to be <80 GeV!
- Obviously more is needed

The Phase Transition II



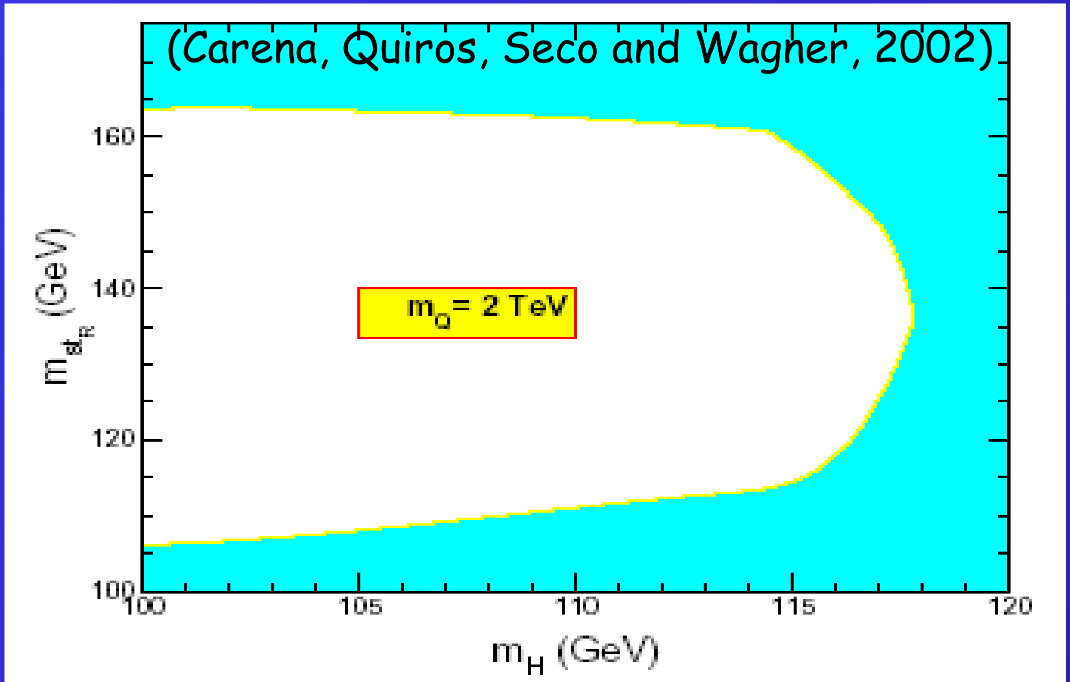
- At critical temperature bubbles of true vacuum nucleate in the sea of false.
- Boundaries are approx. planar bubble walls; sweep through space, eventually percolating



- These boundaries are the site of a large departure from equilibrium if the phase transition is strongly enough first order.
- As they traverse the whole space, each point becomes a site for the production of the BAU

Bounds and Tests

- In supersymmetry, sufficient asymmetry is generated for **light Higgs, light top squark, large CP phases**
- Promising for LHC/ILC!
- Severe upper bound on lightest Higgs boson mass, m_h <120 GeV (in the MSSM)
- Stop mass may be close to experimental bound and must be < top quark mass.



Very nice description of bounds in Dan Chung's parallel talk at the 2004 SLAC LC meeting (Linked from ALCPG cosmology subgroup page)

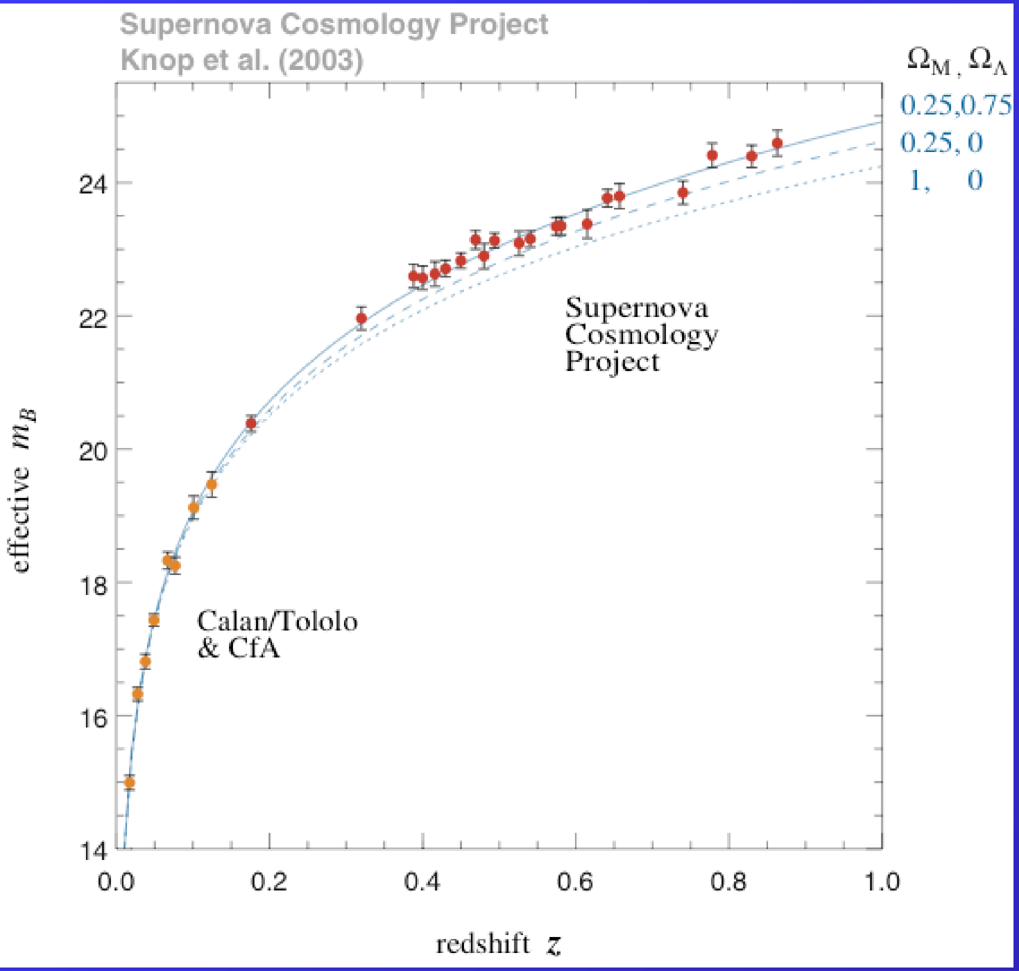
Other Connections

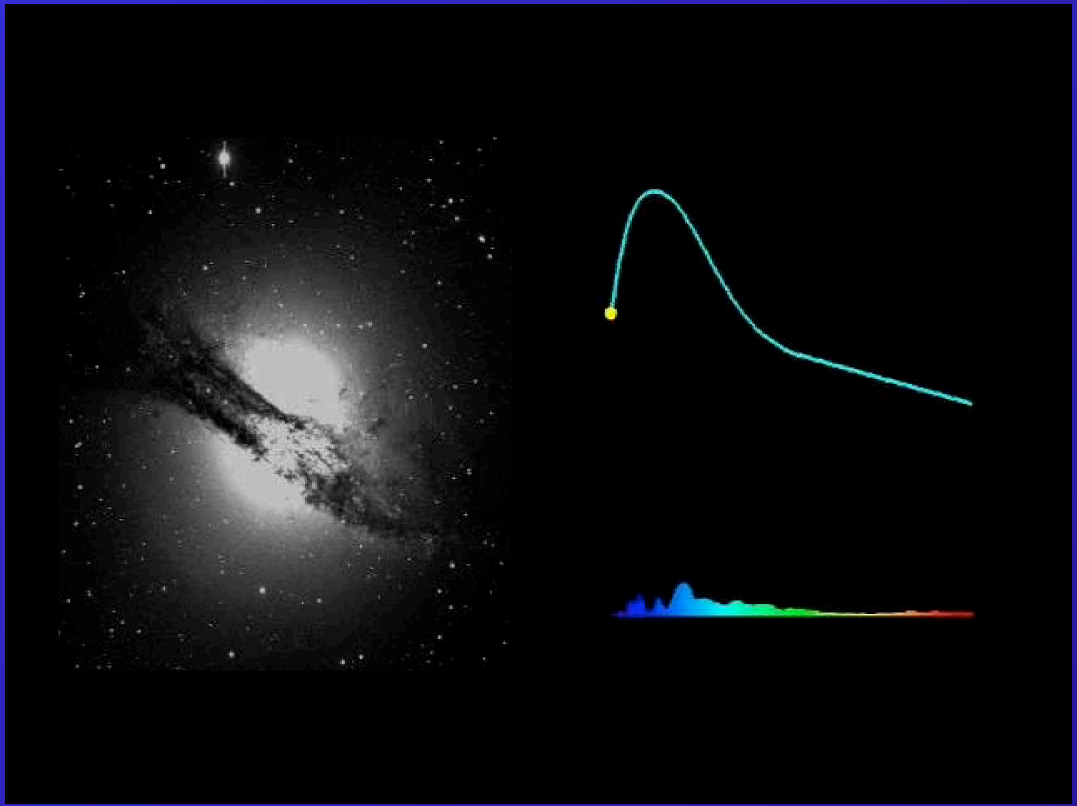
- Another important test for EWBG may come from B-physics - CP-violating effects (but not guaranteed at B factories)
- Essential to have new measurements of CP-violation, particularly in the B-sector

- Important to remember that BG may be due to different and entirely new TeV scale physics (e.g. Langacker et al. Z' model)

- What can colliders and other particle and nuclear physics experiments tell us about BSM physics, particularly CP-violating phases? [e.g through EDM measurements]

Dark Energy





- Positive pressure matter slows the expansion
- Negative (enough) pressure speeds up the expansion

(like throwing up a ball and having it accelerate away!)

Dark Energy - Theory

Evolution of the universe governed by Einstein eqns

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 \propto \rho$$ The Friedmann equation

$$\frac{\ddot{a}}{a} \propto -(\rho + 3p)$$ The "acceleration" equation

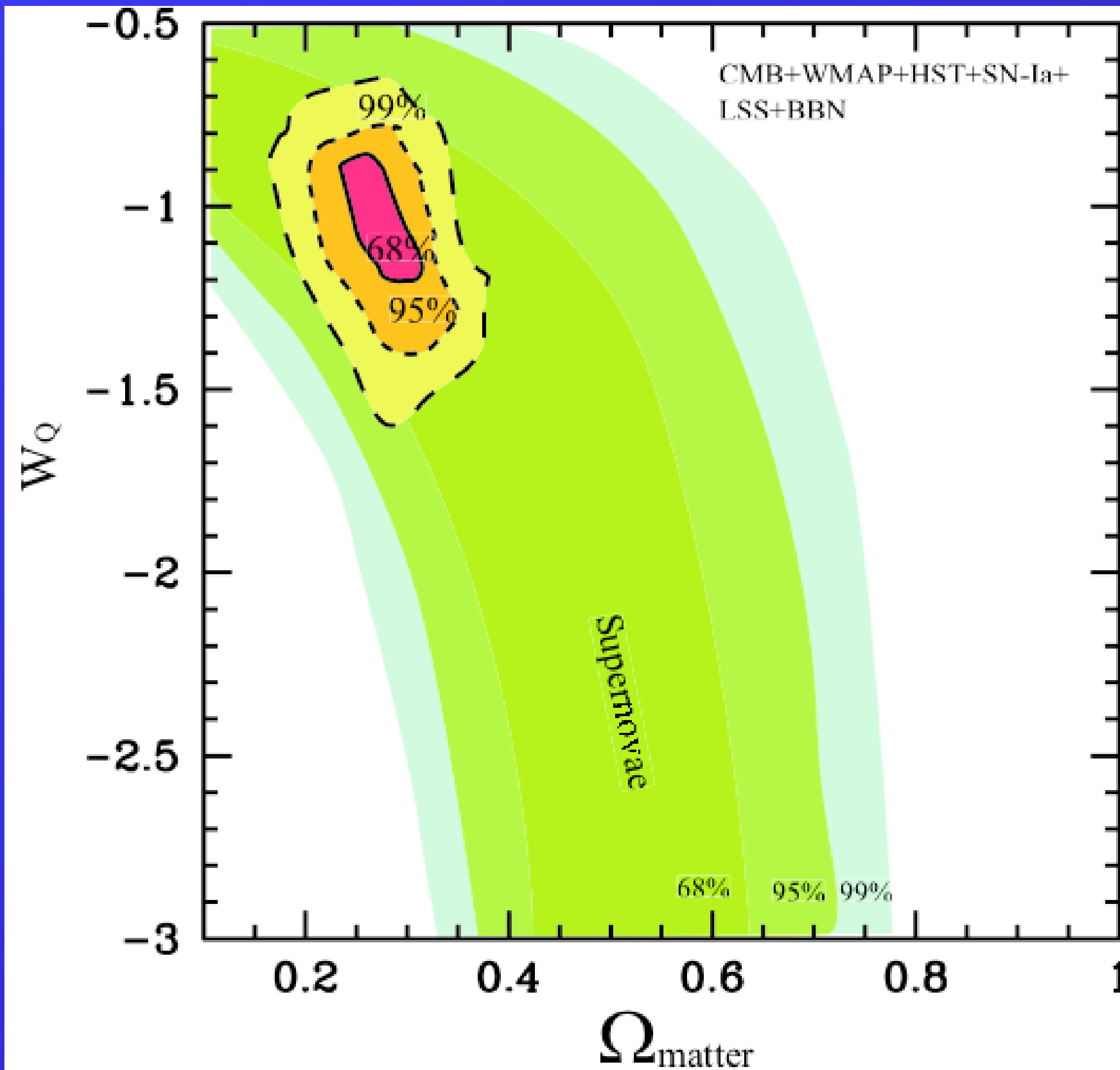
Parameterize different types of matter by equations of state: $p_i = w_i \rho_i$

When evolution dominated by type i, obtain

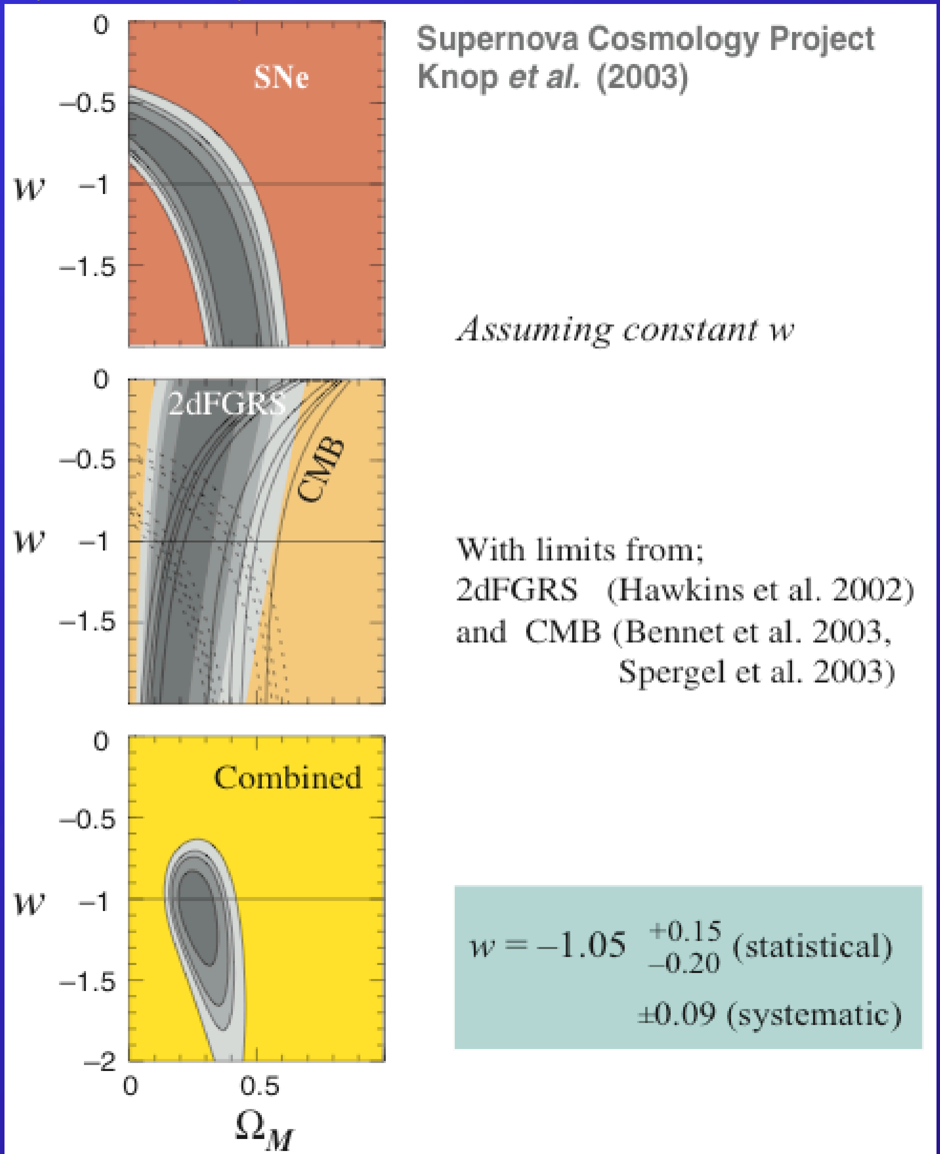
$$a(t) \propto t^{2/3(1+w_i)} \qquad \rho(a) \propto a^{-3(1+w_i)} \qquad (w_i \neq -1)$$

Data on w_Q

Basically measuring (luminosity) distance as fn of redshift.



[Melchiorri, Mersini, Odman and M.T. (2002)]



[Knop et al. (2003)]

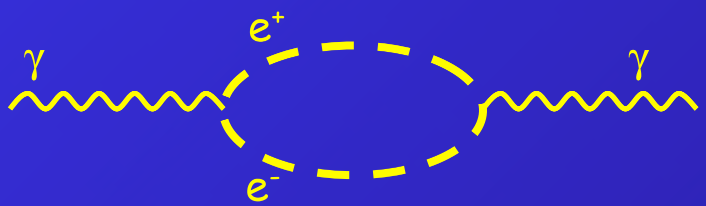
An Example - Λ

- We know essentially nothing about dark energy
- Tied to our ignorance about the cosmological constant.
- Exploration of Higgs boson(s) and potential may give insights into scalars, vacuum energy, SUSY breaking.

- Vacuum is full of virtual particles carrying energy.
- Should lead to a constant vacuum energy. How big? - ∞

BUT…

- While calculating branching ratios - easy to forget SUSY is a space-time symmetry.
- A SUSY state $|\psi\rangle$ obeys Q $|\psi\rangle=0$, so H $|\psi\rangle \propto \{Q,Q\}\, |\psi\rangle=0$
- Only vacuum energy comes from SUSY breaking!



$$\rho_\Lambda \sim M_{SUSY}^4$$

Still 10^{60} too big!

New Gravitational Physics

Carroll, Duvvuri, M.T. & Turner, **Phys.Rev.D70:043528 (2004) [astro-ph/0306438]**

Consider modifying the Einstein-Hilbert action

$$S = \frac{M_P^2}{2}\int d^4x\sqrt{-g}\left(R - \frac{\mu^{2(n+1)}}{R^n}\right) + \int d^4x\sqrt{-g}\,L_M$$

(I'll focus on n=1 for most of this)

Field equation (n=1):

$$\left(1+\frac{\mu^4}{R^2}\right)R_{\mu\nu} - \frac{1}{2}\left(1-\frac{\mu^4}{R^2}\right)Rg_{\mu\nu} + \mu^4\left[g_{\mu\nu}\nabla_\alpha\nabla^\alpha - \nabla_{(\mu}\nabla_{\nu)}\right]\left(\frac{1}{R^2}\right) = \frac{T_{\mu\nu}^M}{M_P^2}$$

With, for cosmology

$$T_{\mu\nu}^M = \left(\rho_M + P_M\right)U_\mu U_\nu + P_M g_{\mu\nu}$$

Problems with Simplest Models

Easy to see model has problems agreeing with GR on scales smaller than cosmology. Can map theory to

$$S \propto \int d^4x \sqrt{-g} \left[\Phi R - \frac{\omega}{\Phi} \partial_\mu \Phi \partial^\mu \Phi - U(\Phi) \right]$$

i.e., a Brans-Dicke theory, with a potential that we may ignore, with $\omega=0$

But solar system measurements constrain $\omega>40000$

However, more complicated models seem to work OK

More General Actions

Carroll, De Felice, Duvvuri, Easson, M.T. and Turner, [**astro-ph/ 0410031**]

$$S = \frac{M_P^2}{2}\int d^4x\sqrt{-g}\,[R + f(R,P,Q)] + \int d^4x\sqrt{-g}\,L_M$$

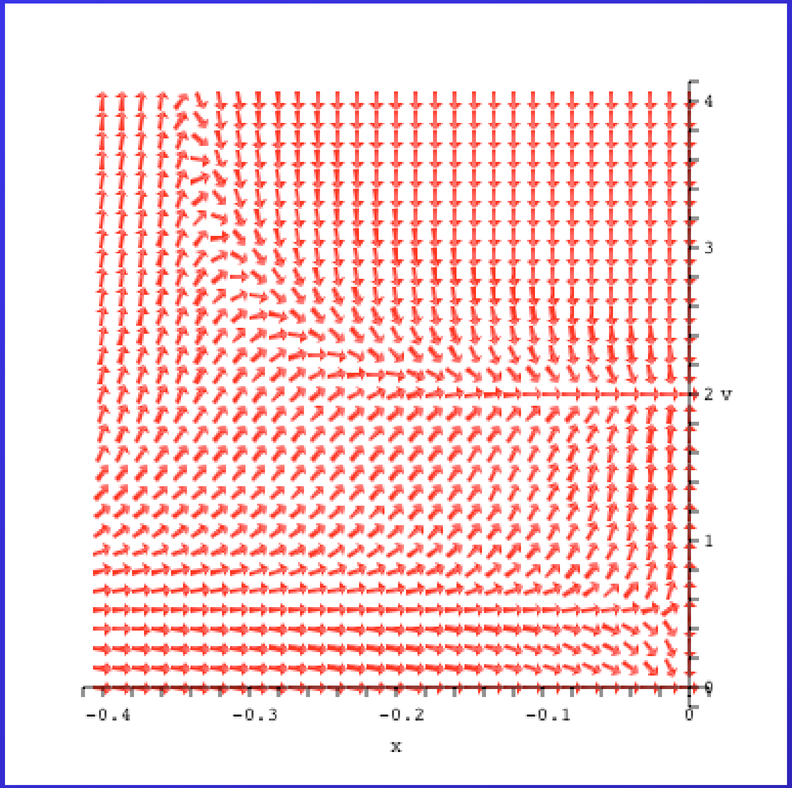
$$P \equiv R_{\mu\nu}R^{\mu\nu}$$

$$Q \equiv R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$$

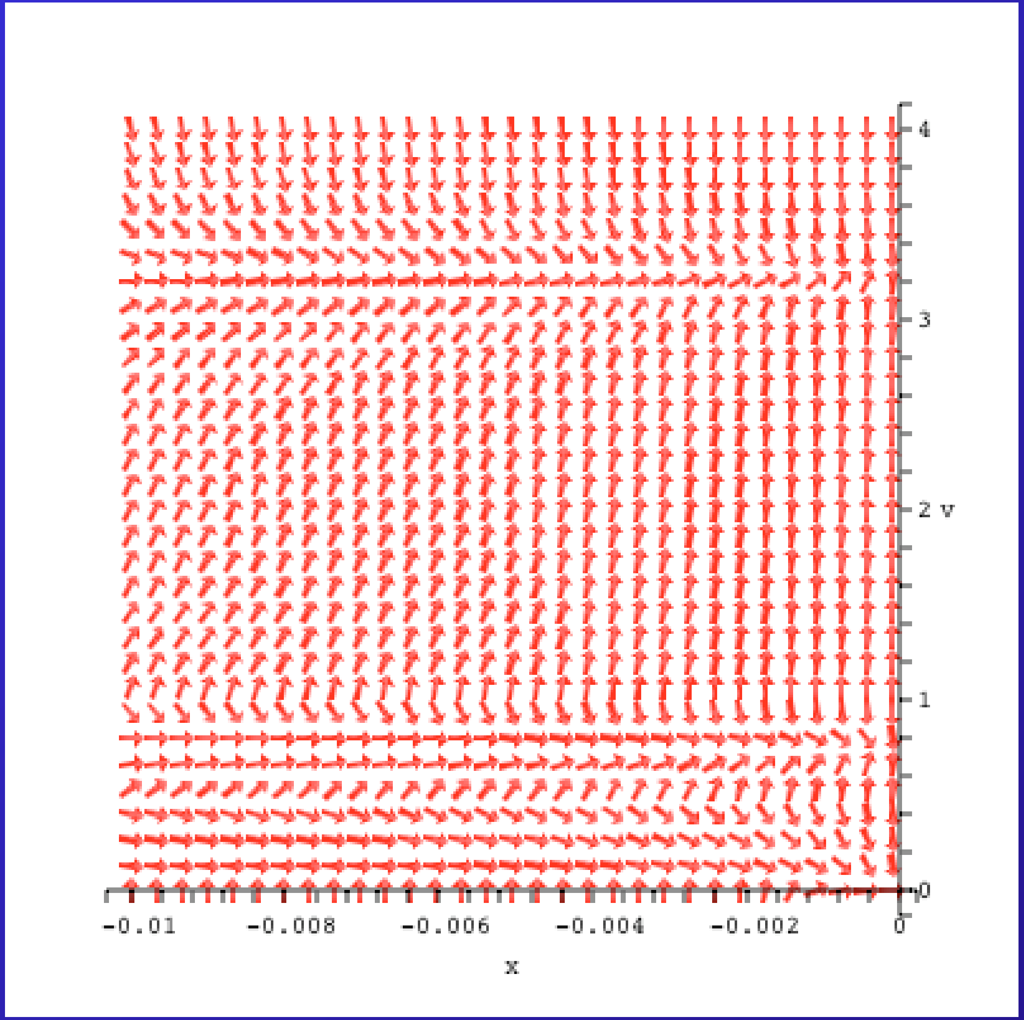
$$x \equiv -H(t)$$

$$y \equiv \dot{H}(t)$$

$$y = -\frac{x^2}{v(x)}$$



Original 1/R model



$$f = 1/P$$

Modified Gravity Status

- Have demonstrated that cosmic acceleration may arise from the gravitational sector.
- Simplest model fails solar system tests, but more complicated models seem to work OK

Much more work could be done

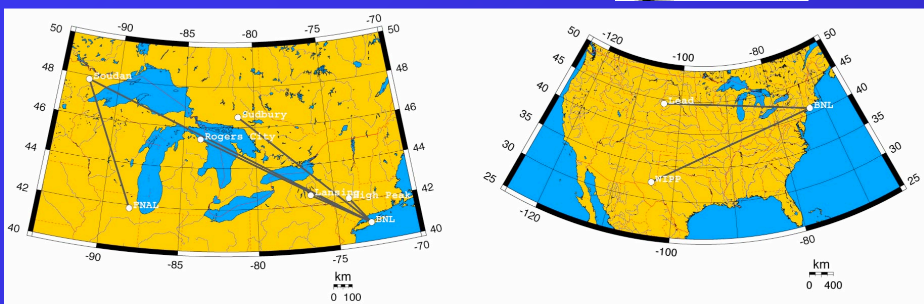
- perturbations,
- z-dep of w,
- dependence on initial conditions
- gravitational waves,
- and a lot more.

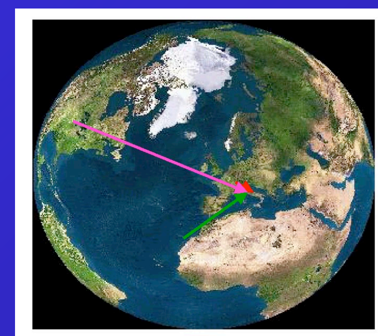
The Future

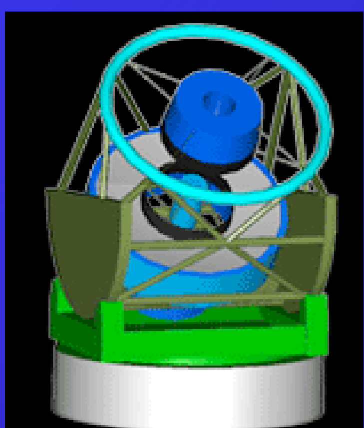
LHC - THE LARGE HADRON COLLIDER

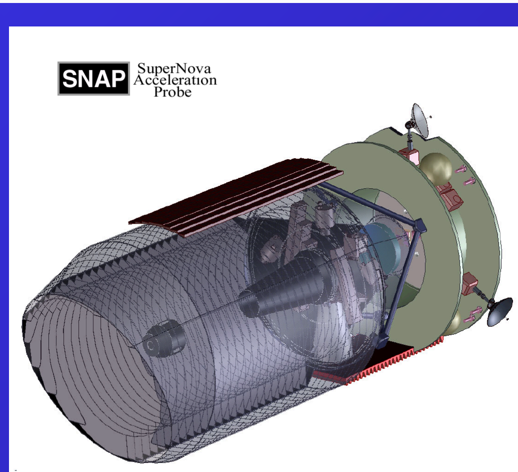
BELLE

LHCb









advancedligo

LIGO

LISA Opening a new window on the Universe

Laser Interferometer Space Antenna

CDMS

PLANCK

... and many, many more...

Final Comments

- Cosmology provides strong, independent arguments for new physics at the TeV scale - primarily from the observation of a BAU and evidence for dark matter.
- There is a marvelous opportunity for the interplay between precision cosmological observations, terrestrial dark matter searches and particle physics experiments (e.g. LHC/ILC) to yield an understanding of the universe at $t \sim 10^{-8}$ s, comparable with that obtained through BBN at $t \sim 10$ s.
- It is entirely possible that new gravitational physics is responsible for some of our mysteries. But this possibility is highly constrained already.
- Clearly, we all have a lot of work to do.

-Thank You -